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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

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TO: J. M. BOSWELL
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E. F. STURCKEN E. F. Sturcken

MECHANICAL PROPERTIES OF IRRADIATED 6063 ALUMINUM SLEEVE HOUSINGS

INTRODUCTION

The effects of radiation on the mechanical properties of 6063 aluminum septifoils and quatrefoils was first reported by Bergstresser[(1)] in 1962. Some hardness measurements were also reported for a 6061 aluminum septifoil by McCaskey[(2)] in 1965. Bergstresser found increased yield strength, ultimate strength, hardness, and susceptibility to cracking, but concluded that the changes in properties posed no serious difficulties during charging and discharging operations.

Because of the advent of reusable components, e.g., the Mark XII and XIIA outer housings, and Universal Sleeve Housings, at much higher assembly powers, a comprehensive program[3] was undertaken to measure mechanical properties of 6063 aluminum to establish safe service lives for the new components. The use of 6063 aluminum for the Mark 18A target housings in Cf-I further extended the need for mechanical property data to determine whether strength losses or brittle behavior would occur during reactor operation, discharge handling, or during basin cutting operations to remove the active core.

The program gained additional impetus by the report of the failure of the 8001 aluminum cladding on a group of SRP-HFIR Target Tubes[4,5] after a fast neutron irradiation of $1.1 - 1.5 \times 10^{22}$ n/cm^2, E>0.8 Mev. ORNL studies indicated that the target elements failed because the cladding ductility was so reduced by the effects of irradiation that it could not yield to accommodate internal pressure generated by swelling of the plutonium oxide target material.

In the present study samples of actual reactor components were tested, rather than prepared specimens, to eliminate variables that normally surround the use of prepared specimens. The 6063 aluminum samples were taken from two Mark 18 sleeve housings from the Cf-I campaign; these tubes represented the most highly exposed material available.

SUMMARY

Measurements of yield strength, ultimate strength, elongation to fracture,and hardness were made on tensile specimens from 6063 aluminum housings irradiated to fluences in the range 3.2 to 7.8×10^{21} n/cm^2, E>0.8 Mev.

For specimens with the maximum fluence tested at room temperature, the yield strengths increased from 24,000 to 55,000 psi, the microhardness increased from 72 to 127 DPH, and the elongation to fracture decreased from 10.4 to 7.2%. Annealing studies showed that the irradiated materials retained the strength gained during irradiation at temperatures up to 300°F (149°C) and times up to two weeks. Studies of ductility as a function of test temperature showed that, for maximum irradiation, there was a minimum in the ductility (3% elongation to fracture) at 400°F (204°C).

In general, the mechanical properties of the 6063 aluminum are still quite good after irradiation except that the shape of the stress strain curves indicate an increase in notch sensitivity. The importance of this factor will be determined in future experiments.

EXPERIMENTAL PROCEDURES

Sampling Scheme and Irradiation Conditions

Tensile specimens were cut from the longitudinal direction of tubular sections of irradiated and unirradiated Mark 18 sleeve housings employing an underwater punch and die machine (see Appendix) that was designed for these experiments. Specimens were taken from regions of high fluence which were adjacent to the fuel core during reactor operation. Control samples were obtained from regions of low fluence above the fuel core and from unirradiated sleeve housings.

The average neutron exposure at the midplane of the housings was calculated by Gorrell[6] for the Cf-I charge. Using the ratios determined by an Axial Power Monitor, the fluence was estimated at regions above and below core midplane. Accuracy of these calculated fluences is estimated to be ±15%.

Tensile Tests

Testing was performed out-of-cell on an Instron Tensile Tester at a strain rate of 0.02 inch/min. Air-operated grips were used for the tests to minimize radiation exposure. The grip faces were machined to match the curvature of the tensile specimens and pins were added to the faces to reduce slippage during the test. An environmental chamber having a temperature range of -100°F to 600°F (-73° to 316°C) was used for the high temperature tests and the specimens were held at temperature for twenty minutes before test. Duplicate or triplicate samples were used except where noted.

The yield and ultimate load values were obtained from the strip chart records of the test. The elongation to fracture was obtained by scribing one-inch gauge length marks onto the samples before testing. Following the test, the fractured parts were reassembled and the length increase was measured. This fractional increase expressed in percent is the total elongation to fracture.

Hardness Tests

Diamond Pyramid Micro-hardness (DPH) tests were performed on metallographic samples of 6063 aluminum housings using a Tukon Hardness Tester. The DPH value is defined as the load per unit area of surface contact expressed in units of kg/mm^2. For all the tests, a load of 0.5 kg and a dwell time of 15 seconds was used. The average of at least five indentations was used for each sample.

RESULTS AND DISCUSSION

Mechanical Properties Versus Fluence

The results of the tensile and hardness tests are summarized in Table I. The yield and ultimate strength and the elongation are plotted as a function of fluence in Figure 1 for tests at room temperature and 212°F (100°C). These temperatures were chosen because they include the range of reactor operating temperatures for the housings. Figure 1 shows that, for the maximum fluence and room temperature testing, the yield and ultimate strengths increased about 85% while the ductility decreased by about 30%. In the 212°F (100°C) test the strength increased about 80% and the ductility decreased 45%.

A similar increase in strength and decrease in ductility due to neutron irradiation[4,5] has been observed in other aluminum alloys. It does not appear severe enough to limit the service life of the housings. However, the small difference in stress level between yield and ultimate strength is of some concern since it indicates that negligible work hardening occurred, and hence the material would fail at stress levels only slightly above the yield point. For example, at 212°F (100°C) there is only about 1000 psi difference between the yield and ultimate strengths.

The essential difference in the manner of yield between the irradiated and unirradiated specimens is demonstrated by the shape of the stress-strain curves and the photographs of the fractured specimens in Figure 2. The unirradiated specimens undergo considerable necking so the stress-elongation curve "bends down" and the failures occur at an apparently lower stress because of the reduced area of the specimen. The irradiated specimens undergo less strain and the strain is quite uniform, so they fail at stress levels near the ultimate stress.

Mechanical Properties Versus Test Temperature

The mechanical properties are plotted as a function of test temperature in Figure 3. Note that the irradiated specimens are considerably stronger over the entire temperature range; for example the irradiated specimens are stronger at 400°F (204°C) than are the unirradiated specimens at 75°F (24°C). The ductility of the irradiated specimens is lower over the entire range tested and has a minimum (3% elongation to fracture) at about 400°F (204°C). The unirradiated specimens have a ductility minimum (10% elongation to fracture) at about 75°F (24°C). This shift in the ductility minimum suggests that irradiation has caused the recovery and recrystallization temperatures of the 6063 aluminum to shift upward by several hundred degress Fahrenheit.

Hardness Versus Fluence and Annealing Temperature

The change in hardness is plotted as a function of fluence in Figure 4. In addition to the Mark 18 housings, data are also shown for Mark XII housing tubes and septifoils from the Curium II campaign[7] and a section of the mechanical "rabbit" tube that operated in the curium and californium campaigns. Note that the hardness rises steeply with fluence up to about 4×10^{21} n/cm^2 then begins to saturate, i.e., level off in the range 4×10^{21} to 10^{22} n/cm^2. A plot of change in yield strength versus change in hardness (Figure 5) is approximately linear with a proportionality ratio of about 3, in agreement with work by Tabor[8] on other metals. The linearity relationship is useful since it is easier to measure hardness than yield strength. It should be noted, however, that the hardness value probably does not give any indication of the ductility.

Studies of the effects of annealing on hardness were performed on specimens irradiated to 5×10^{21} n/cm^2. The results, Table II, show that following annealing at temperatures up to about 300°F (149°C) and for times up to 14 days the 6063 alloy retained most of the strength gained during irradiation. On the other hand, annealing at 510°F (266°C) caused the material to lose all its radiation induced strength in less than five hours and begin overaging to lower strengths in a manner similar to unirradiated alloys.

Mechanism of Radiation Damage

In general radiation induced changes in mechanical properties are caused by resistance to plastic flow in a metal due to the presence of defects such as interstitial and vacancy clusters, dislocations, stacking faults, voids, and transmutation products.

The microscopy studies of aluminum showed that irradiation produced a dense dislocation network and an increase in the size of the Mg_2Si precipitate structure, but no voids unless they were smaller than about 50 Å, the resolution of the microscope.

For the maximum irradiation of 9.1×10^{22} thermal neutrons about 1.77 weight percent of the aluminum was transmuted to silicon by the nuclear reaction*

$$^{27}\text{Al}\ (n,\gamma)\ \xrightarrow{\beta}\ ^{28}\text{Si}$$

Additions of excess silicon to Al-Mg_2Si alloys are known to increase their hardness.[9] Hence, the increased strength and hardness and decreased ductility of the aluminum were probably caused by a combination of the transmuted silicon and the radiation induced dislocations.

GBA:CWK:EFS:rbw

*The cross section σ is 0.23 barns.

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2. G. A. McCaskey to R. M. Mousel, "Metallurgical Evaluation of Irradiated Septifoil" REA-C13, August 25, 1965.

3. G. B. Alewine to E. C. Nelson, "Radiation Effects on Reusable Reactor Components" DPST-67-317, May 17, 1967.

4. J. E. Cunningham, "Severe Radiation Damage to Aluminum," ORNL-TM-2138, March 1968.

5. "Analysis of Failure of HFIR Target Elements Irradiated in SRL and in HFIR - An Interim Status Report," ORNL-TM-2236 (February 1972).

6. T. C. Gorrell to G. B. Alewine, "Fast Flux in Cf-I," DPST-69-594 (Secret) November 17, 1969.

7. SRL Monthly Report, DP-68-1-5, p.40.

8. D. Tabor, "The Hardness of Metals," Oxford University Press (1951).

9. S. Ceresara, et al., "Effect of Si Excess on the Aging Behavior of Al-Mg_2Si 0.8% Alloy," Mater. Science Eng. 5, (1969-1970), 220-7.

TABLE I

YIELD STRENGTH, ULTIMATE STRENGTH, DUCTILITY VERSUS FLUENCE FOR 6063 ALUMINUM HOUSINGS

Fluence x 10^{21} n/cm^2 E>.8 Mev	Strength (ksi) Yield 75°F (24°C)	Strength (ksi) Yield 212°F (100°C)	Strength (ksi) Ultimate 75°F (24°C)	Strength (ksi) Ultimate 212°F (100°C)	% Elongation to Fracture 75°F (24°C)	% Elongation to Fracture 212°F (100°C)	Hardness (75°F) (24°C)
0.00	24.1	23.3	29.4	25.8	10.4	10.9	72.3
3.2	42.5	38.7	45.9	39.6	8.8	9.4	112
4.8	44.7	40.0	48.6	41.3	9.1	8.8	123
5.1	45.0	41.5	49.2	42.9	8.7	9.1	125
7.8	50.4	45.5	54.7	46.8	7.2	6.0	127

TABLE II

ANNEALING vs MICROHARDNESS* OF 6063 Al
($5 \times 10^{21} n/cm^2$, E>0.8 Mev)

	510°F (266°C)		284°F (140°C)		230°F (110°C)	
Time	Control	Irrad.	Control	Irrad.	Control	Irrad.
0 hrs	70	117	70	118	70	119
1 hr	69	83				
5 hrs	60	64				
1 day	51	52				
2 days	47	47		109		
4 days	45	46				
5 days			70	103		
8 days					70	114
14 days			63	102	68	114
16 days	32	40				

*Vickers Diamond Pyramid, 500 g load

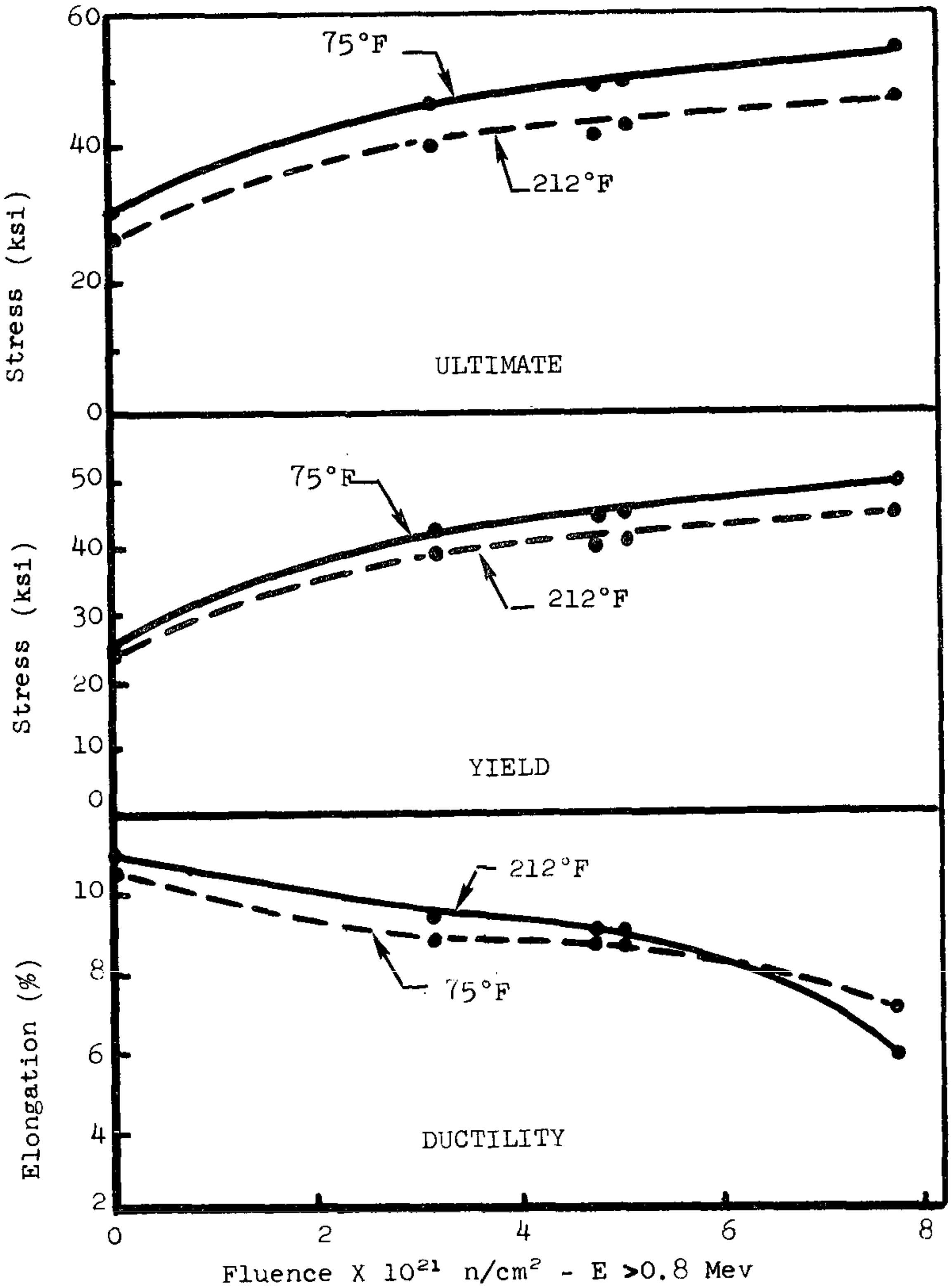

FIGURE 1 - MECHANICAL PROPERTIES vs FLUENCE

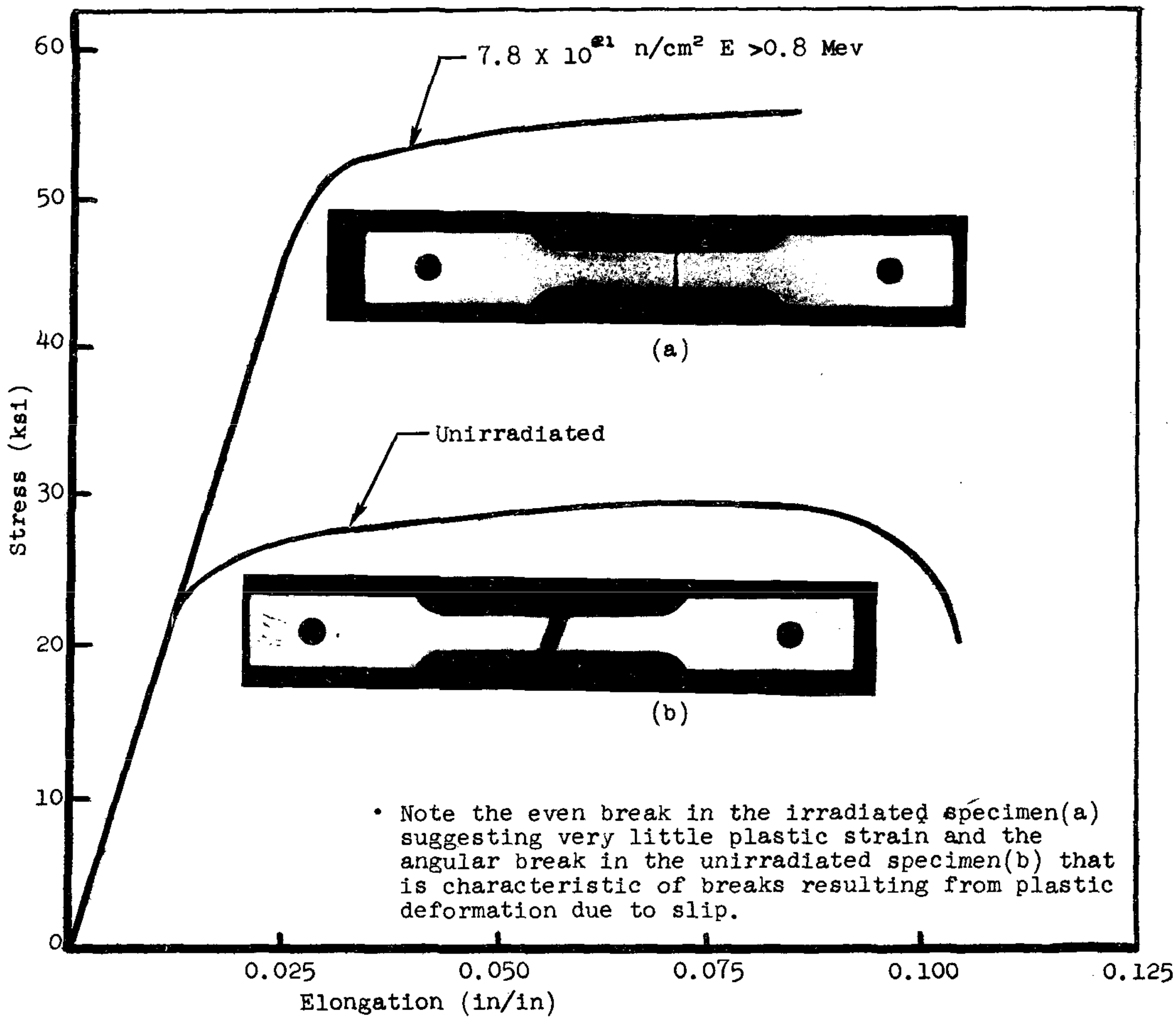

FIGURE 2 - TYPICAL STRESS - STRAIN CURVES FOR IRRADIATED AND UNIRRADIATED 6063 ALUMINUM

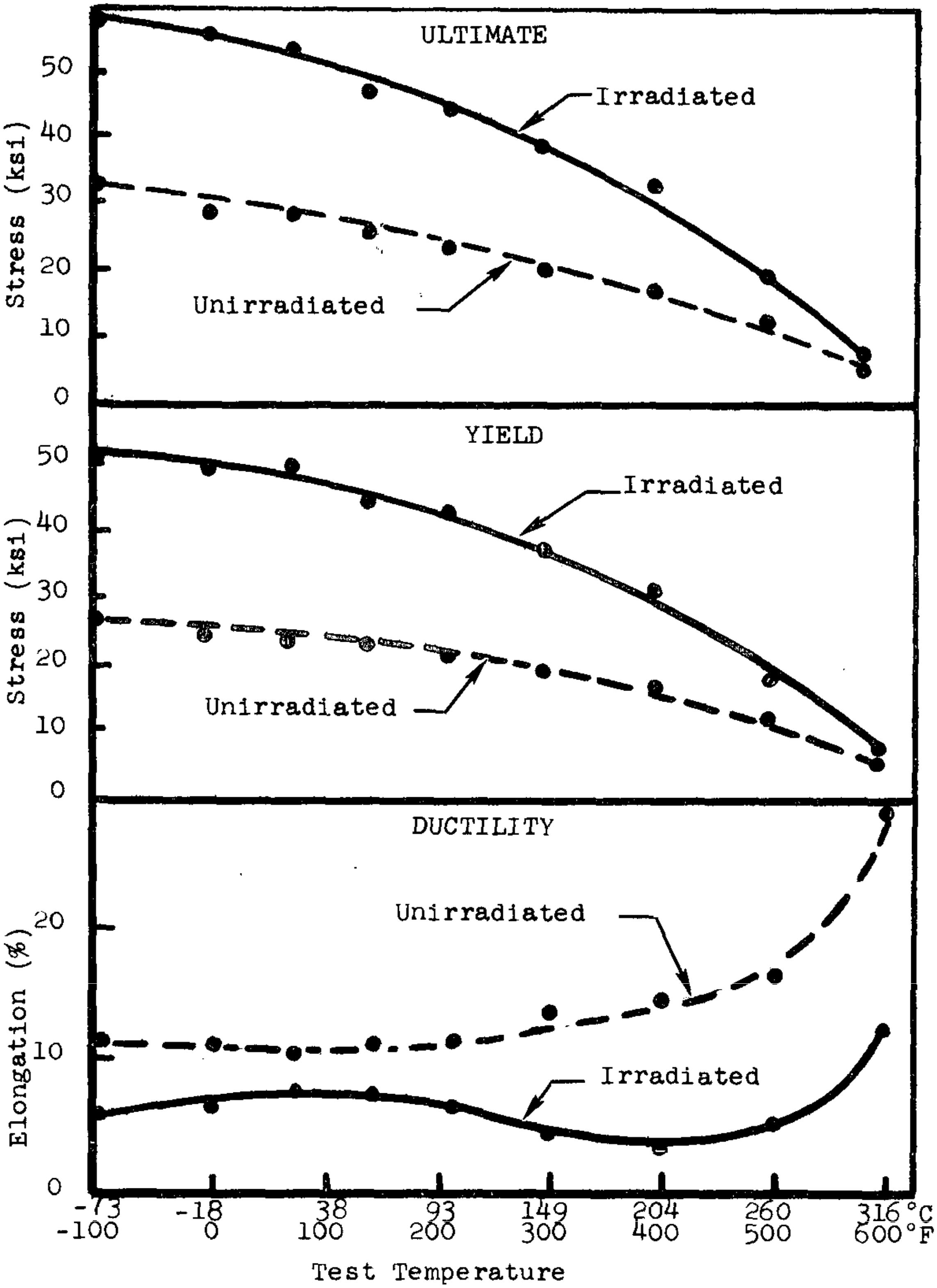

FIGURE 3 - MECHANICAL PROPERTIES VERSUS TEMPERATURE

Specimens irradiated to $7.8 \times 10^{21} n/cm^2$
(1 sample tested per temperature)

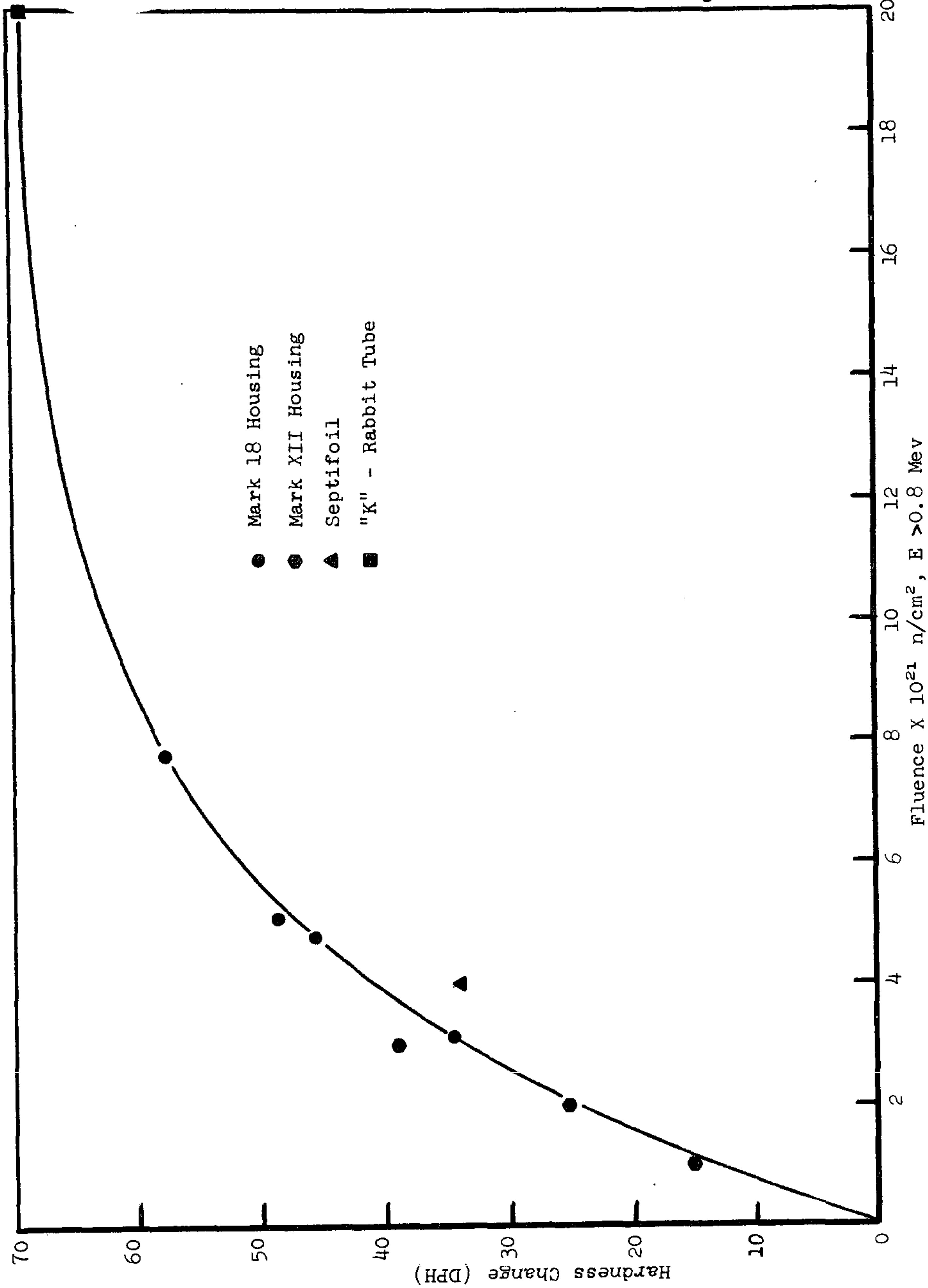

FIGURE 4 - CHANGE IN HARDNESS vs FLUENCE

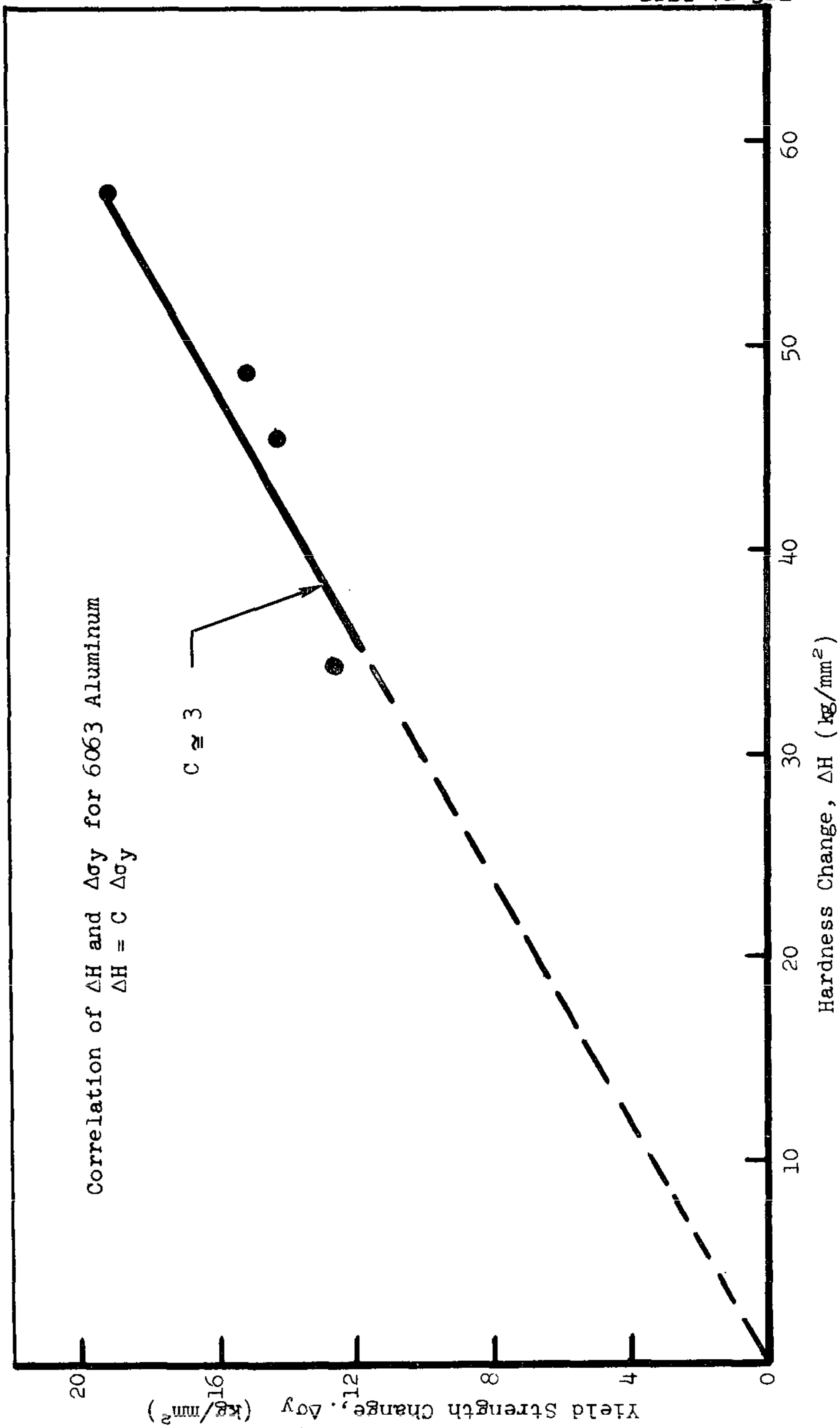

FIGURE 5 - CHANGE IN YIELD STRENGTH vs CHANGE IN HARDNESS

APPENDIX

THE PREPARATION OF TENSILE SPECIMENS FROM IRRADIATED HOUSING TUBES

Tensile specimens were prepared from tubular housing sections sawed with an underwater bandsaw in a RBOF basin. Fully shaped tensile specimens were stamped from the housing sections with a specially designed underwater punch and die machine and precision holes, for gripping, were stamped in the tensile specimens with a hand operated press. The finished specimens were decontaminated by chemically removing a few mills of metal with "brightening" reagent recommended by Alcoa.[1]

Ring Preparation

The irradiated housing tube was divided into 6-inch long segments. The segments were identified with numbers indicating their location with respect to the core midplane, positions above the core midplane are positive and those below the midplane negative (see Figure 1). Each segment selected for specimens was cut from the full tube using an underwater bandsaw in the RBOF basin. These rings were stored on hangers in the basin until stamping operations began.

Tensile Specimen Preparation

The 6-inch long rings (4.110" OD x .050" wall) were placed on the mandrel of an hydraulically operated punch and die machine located under 6 feet of water. G. P. Jones of the Project Department assisted in the design of the punch and die set. Handling of the rings was done with underwater tongs. Vertical grooves in the mandrel provided clearance for the internal ribs and also a means of indexing the ring section for uniform spacing of the specimens in the ring.

A tool steel punch mounted on a die alignment shoe was actuated by a 10 ton cylinder powered by a hand operated hydraulic pump (Figure 2). Twelve specimens were sheared from each ring section. Both the punch and the die were curved to fit the shape of the housing tube and this curvature was maintained in the finished specimen (Figure 3). Gage width and length dimensions meet ASTM Standard E8-66 for subsize rectangular specimens.

Stamped specimens dropped from the die down through the center of the mandrel to a basin storage can positioned under the die. Each can, containing the 12 specimens from a ring section was labeled with the reactor coordinate number to identify the tube and also with the positive or negative axial position (Figure 4). C. M. Baldwin of the Separations Department assisted in planning and executing the operations in RBOF.

APPENDIX

Specimen cans were shipped to SRL in 450 pound lead shielded casks for cleaning and the stamping of the grip pin holes. A special punch and die in a hand operated one ton press placed two precision holes simultaneously in the ends of the specimens (Figure 5). The finished specimens were decontaminated by placing them in a solution of 1 part HNO_3 to 20 parts H_3PO_4 for 1 to 2 minutes at 93°C then rinsing them in distilled water.

(1) E. F. Sturcken and G. B. Alewine to P. H. Permar-S. Mirshak, Trip Report, "Visit to Alcoa Research Laboratories," March 1968.

APPENDIX

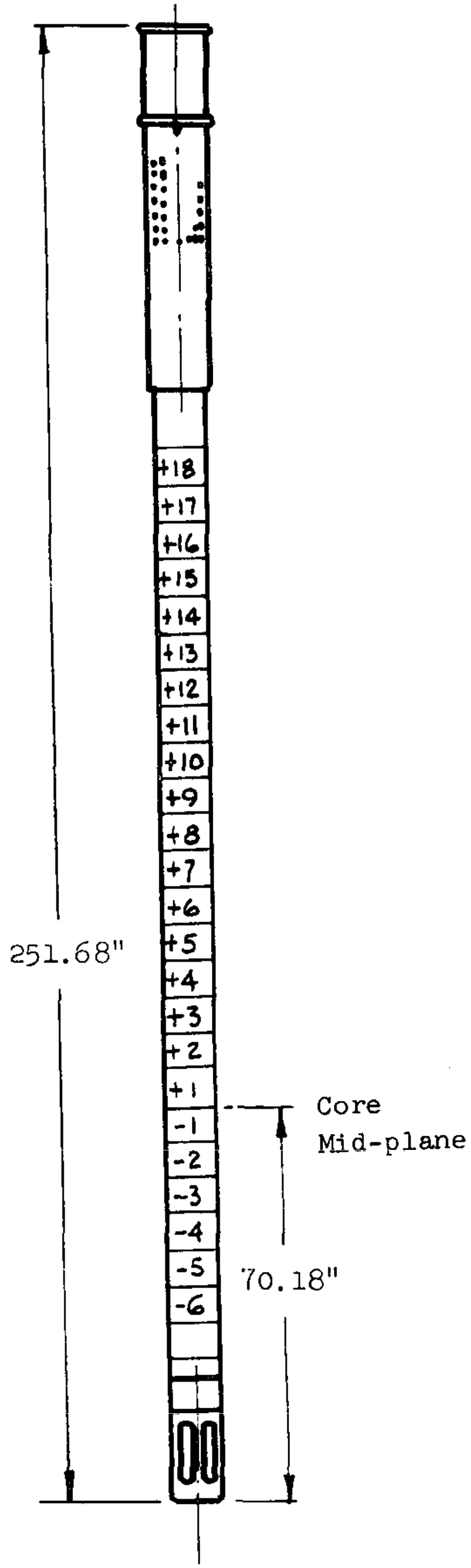

FIG. 1. SPECIMEN LOCATION

APPENDIX

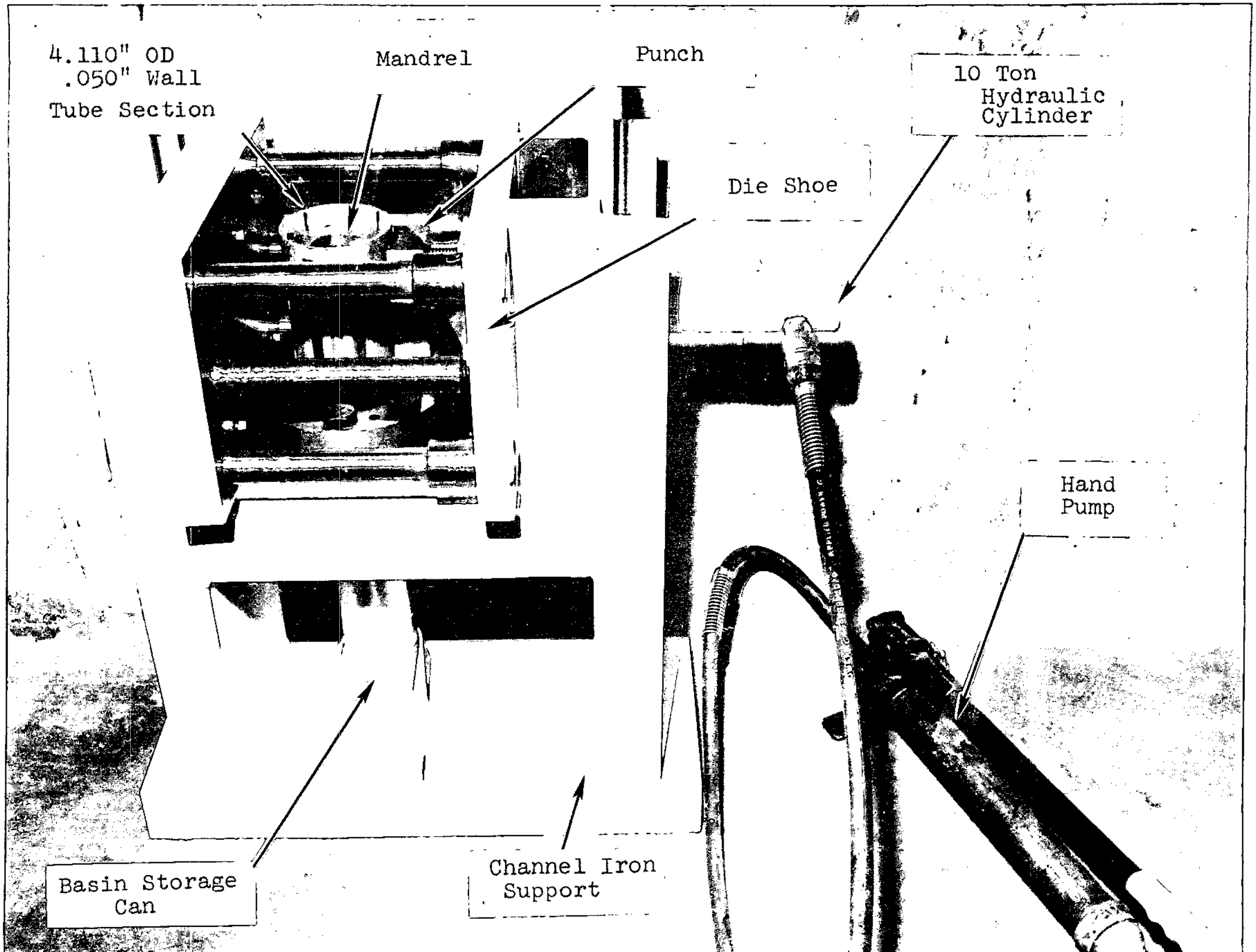

FIG. 2 HYDRAULIC TENSILE SPECIMEN PUNCH AND DIE

APPENDIX

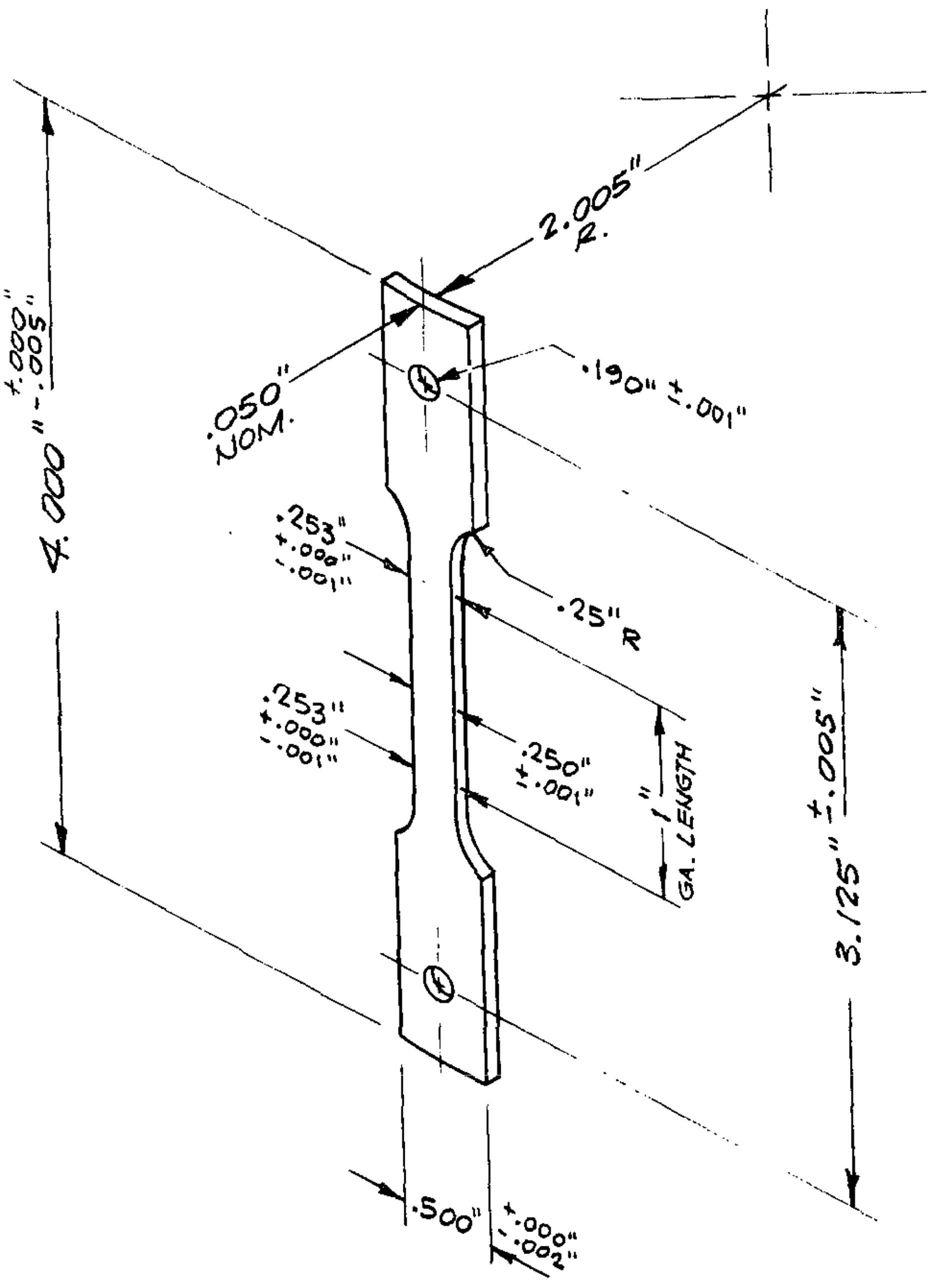

FIGURE 3

TENSILE SPECIMEN

APPENDIX

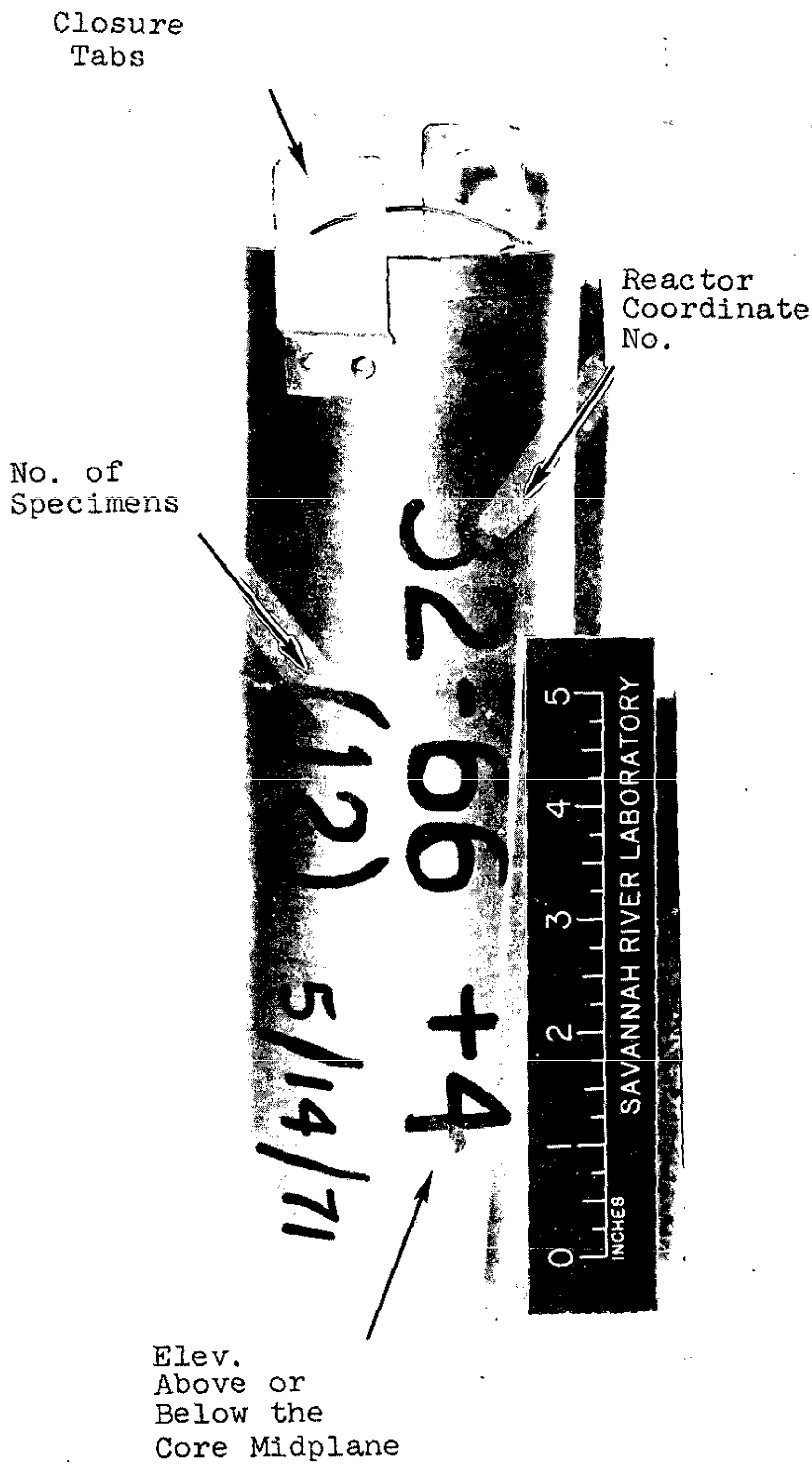

FIG 4. STORAGE CAN

APPENDIX

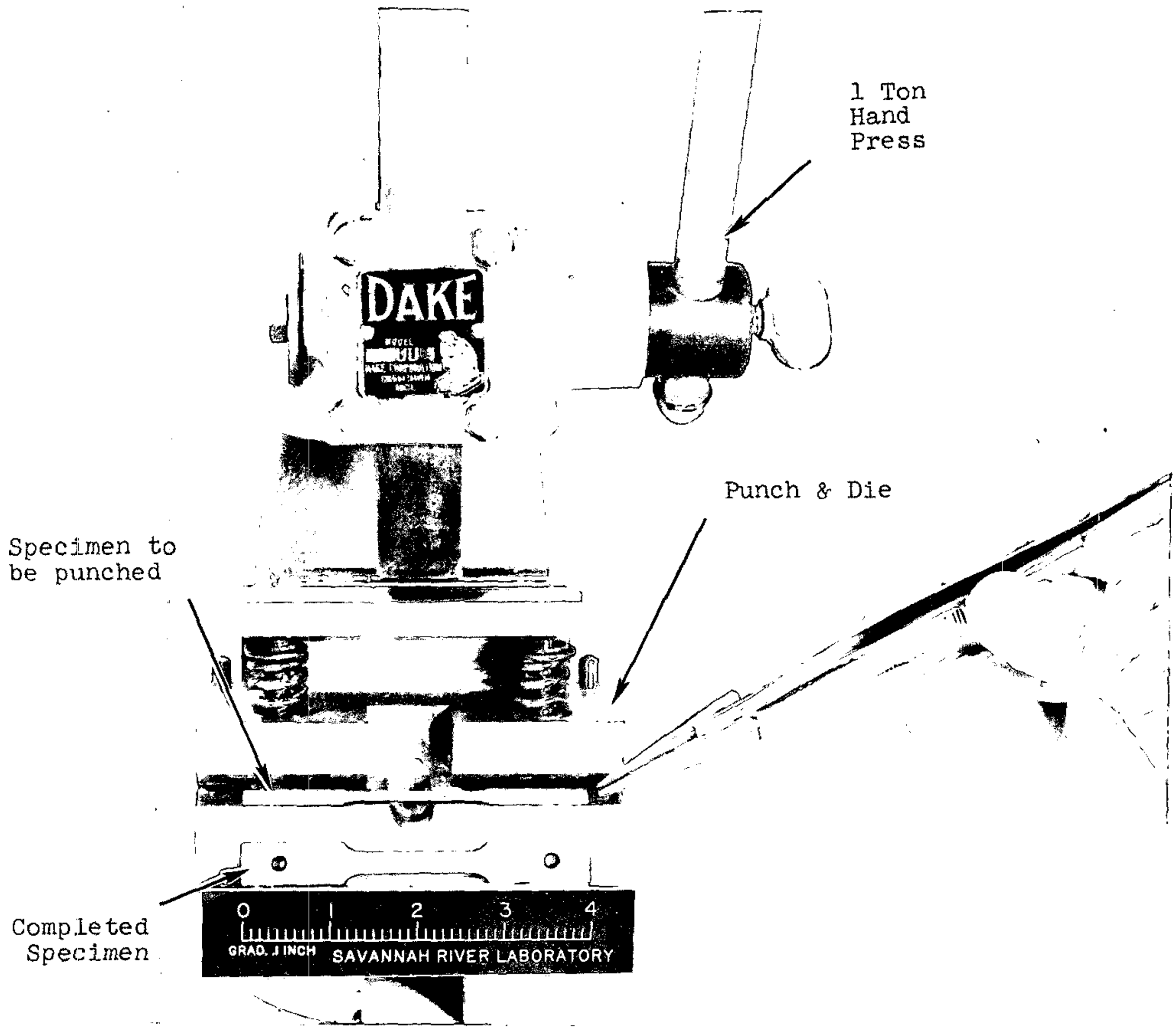

FIG. 5. PUNCH AND DIE FOR GRIP PIN HOLES